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STABILITY AND PERFORMANCE CHARACTERISTICS OF A CRUCIFORM GETOL

by

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SUMMARY

A GETOL model utilizing ground effect under the fuselage and wings (cruciform configuration), tested on the Princeton University Long Track Facility and on a static test stand is reported upon herein.

The model, free in hover, was slowly accelerated to a speed of 37 feet per second. A considerable increase in altitude was observed at the maximum speed even at zero angle of attack. Within the limits of accuracy of the measurements taken (about 10% of the initial hover altitude) there was no loss in altitude observable at any point during the acceleration. A gain in altitude, indicating wing lift, is evident beginning at about 8 to 15 feet per second depending on the configuration and angle of attack.

The biggest percentage height gains came from only wing blowing at a positive angle of attack; however, the model had higher hover heights with only the fuselage slots open seemingly due to less efficient internal wing ducting and lower skirts on the fuselage.

The static tests seemed to indicate that the cruciform configuration is stable in both roll and pitch up to $^{h}/mac$ ratios of .96 which was the maximum altitude tested. As might be expected the stability decreased with increasing altitude. Of prime interest was the fact that there seemed to be more roll stability with the wing slots closed than would normally be expected in a GEM without wings. A similar small pitch stability was evident with the fuselage slots closed. This would indicate that even non-blowing external surfaces might help improve the static stability of a GEM.

List of Symbols and Dimensions

h	inches	model height
mac	inches	mean chord (6.25)
S	ft^2	reference area
q	lb/ft^2	dynamic pressure
A'	—	augmentation factor = $\frac{L}{L_\infty}$
L	lb	measured lift above a ground plane
L_∞	lb	measured lift - no ground plane
ϕ	degrees	roll angle
α	degrees	pitch angle of attack
$C_{\ell'}$	—	rolling moment coefficient
C_m	—	pitching moment coefficient
C_μ	—	blowing momentum coefficient

Table of Contents

I. Introduction

Most ground effect machines have been designed, for performance considerations, to have a high ratio of base area to perimeter length, resulting in a circular or slightly less efficient rectangular shaped base. In studies carried out at Princeton University, (Ref.1) it was found that although performance suffered with decreasing base area to perimeter length it was not always as drastic a loss as anticipated. Also it was found that a rectangular configuration tended to be more stable about its short axis and more unstable about its long axis. Therefore in consideration of the natural fuselage-wing configuration of the airplane Mr. T. E. Sweeney suggested a cruciform base shape for a GETOL to obtain stability about both axes. (see Fig.1)

Although such a GETOL would most likely have a forward facing fan, it was decided (for purposes of simplicity) to construct the model with a horizontal inlet atop the fuselage. This decision seemed justifiable since neither drag or pitching moment were of consideration in the forward flight experiments. It was also decided that for the real configuration a skirt about the base of the fuselage would increase performance and keep the structually more delicate wings higher off the ground. This decision has since been somewhat regretted since the effect of the wing, being further off the ground, is diminished. However, it did point up the question of whether it would be efficient to put full blowing in wings if they are to be higher off the ground than the fuselage.

II. Model Description

The model used in these studies, consisted of a box shaped fuselage with a low wing and high twin tail assembly. Figures 2 & 3 show the model and the static test stand used to measure the rolling and pitching moments.

Pertinent external model dimensions are given in Figure 3, while other dimensions are presented here.

<u>Base Areas</u>

Total base area	415.4 sq.in.
Wing base area	215.6 sq.in.
Fuselage base area	199.8 sq.in.
Base area with wing root and tip jets closed	317.7 sq.in.
Aspect Ratio	7.6
Wing span	45 inches

<u>Jet Areas</u>

Total jet area - everything open	60.28 sq.in.
Wing root jets closed	55.31 sq.in.
Fuselage jets only open	24.84 sq.in.
Wing and wing root jets open	40.41 sq.in.
Wing root and tip jets closed	36.17 sq.in.

The wing jet is .44" wide and the fuselage jet is .38". The wing chord, measured from the centerline of the leading edge jet to the centerline of the trailing edge jet is 6.25". The perimeter around the fuselage - measured at the centerline of the jets is 66.75", around the wing it is 47.06". For the cruciform configuration, wing root slots closed, the perimeter is 101.31". Two wing loading conditions were

tested by changing the basic model weight of 15.0 lb to 10.75 lb using a counter weight.

A sheet metal skirt fitted around the fuselage extends .375" below the fuselage base and directs the air flow inward at an angle of 45^{o} except at the wing roots where there are no skirts and the flow angle is 0^{o}. Air flow from the wing jets is directed inward at a 30^{o} angle by the internal geometry of the wing slots. The absence of a skirt around the wing jets gives the wing an effective altitude of .375" when the fuselage skirt is on the ground.

A one horsepower electric motor was used to turn a 7.5", 4 bladed fan for both the long-track and the static tests.

III. Test Procedure

This experiment was conducted in two parts; (1) the long-track tests to determine performance in forward flight, (2) the static stability studies done on the static test stand.

Speed runs were conducted on the long track with the model starting from rest in free hover and slowly accelerating to a maximum velocity of 37 feet per second. Five different configurations were obtained (see Fig.4) by closing off some of the peripheral jet. Data was taken for each configuration at 0 and 2.4 degrees angle of attack from 0 to 37 feet per second during slow accelerations and decelerations. The maximum angle of attack was limited by the hovering capability of the model. The data taken consisted of measuring the altitude of the model above the floor and its forward speed. All data were telemetered from the model to the control room and recorded on tape for reduction at a later time.

Static stability studies were carried out in an effort to determine the GETOL hovering stability characteristics. The model was mounted, inverted, on a modified wind tunnel balance below a moveable ground plane. Four heights of one, two, four and six inches were chosen at which the model was rotated in pitch and roll through plus and minus nine degrees. At the lowest height the size of the model prevented its rotation through more than three degrees. A strain-gage bridge network was used to measure the forces. All moments were reduced to coefficient form and referenced to the longitudinal and lateral axes of the model.

IV. Discussion of Results

A. Performance in forward flight

The Long Track studies were undertaken in an effort to obtain lift data on such a GETOL in forward flight.

Figure 5 is a table showing the pertinent performance data taken from the long track phase of the tests. The values for C_μ were obtained from the static mV_j for each configuration and are given for the maximum velocity attained, 37 feet per second. This figure also shows that for all the configurations tested the maximum hovering altitude decreases with an increase in the angle of attack.

Figures 6 to 8 are plots of an over-all lift parameter qS/W versus h/mac for all five configurations tested at two wing loadings and angles of attack of 0° and 2.4°.

A prime area of interest was the possibility of a loss in hover height with increasing speed which has been found on other configurations. However,

despite a careful search for a small altitude decay with speed there seemed to be no such tendency on this cruciform shape irrespective of which slots were used for blowing (see Figs.6,7,and 8). Thus it seems that it is possible with either blowing or non-blowing wings to eliminate the altitude decay with speed normally experienced with pure GEMs. This of course assumes that the forward propulsion system is not bleeding the hover system.

From the data collected it can be concluded that compared to fuselage blowing, wing blowing is not particularly effective in increasing hover height and only seems to be effective at higher speeds (see Fig.6 and 7). There would seem to be two reasons for this. The first reason is that the skirt about the fuselage meant that the wing was operating at a higher effective height off the ground and thus not contributing as high an augmentation factor as the fuselage. Perhaps a better comparison of wing and fuselage effectiveness could have been obtained if the fuselage skirt had not been used. However, in the practical case, as in these tests with balsa wood wings, it is thought that it would be desirable to keep any high aspect ratio wings higher off the ground than the more solidly built fuselage. The second reason for the tendency of the blowing wings to hover lower is that by their nature of being thin and further from the power sources they undoubtedly have a lower internal efficiency than the fuselage. The fact that they have considerably lower total pressure at the nozzle is shown in figure 19. To some extent balancing these effects is the increased circulation lift at the higher speeds where jet flap action becomes effective. Certainly any full scale configuration of this type should consider the above along with the added advantages of a non-blowing wing such as, lower form drag, cheaper

construction and lower weight. Of course some blowing would probably be desired for control, but this would be considerably different than the wing-blowing performance discussed here. If full wing blowing were desired it might be wise to program for greater fuselage blowing at low speeds and greater wing blowing at the higher speeds.

B. Static performance and stability

Static performance and stability characteristics were obtained from the lift and moments taken on the static test stand. Good stability is evident about both axes - for most of the configurations tested.

Figures 10 to 14 show the change in pitch and roll moment coefficient as $^h/mac$ is changed for a given model configuration. Figures 15 to 18 show the best pitch and best roll configurations for each $^h/mac$ used. Straight line averaging was used on this set for simplicity of presentation.

Generally both longitudinal and lateral stability decrease with an increase in $^h/mac$. For most of the cases presented in figures 15 to 18 positive stability is evident; however, a compromise between the most stable roll and the most stable pitch configuration would have to be selected for a satisfactory vehicle. Unfortunately there seemed to be some lack of symmetry in slot blowing which gives pitch and roll moments even in the level attitude; however this should have no effect on the slopes of the curves which indicate the stability.

Of prime interest is the discovery that there appears to be a roll stabilizing factor added to the GEM by the addition of non-blowing wings, (see Fig.11). This figure shows approximately neutral stability for just fuselage blowing which without the wings is quite unstable. Figure 12

indicates about the same thing for pitch stability with only wing blowing. This as yet unexplained phenomenon has turned up in other studies at Princeton of GEM's utilizing wings to shift the center of pressure (Ref.1).

Lift augmentation, shown in Figure 9, forms a fairly uniform set of curves except for the case of only wing blowing which is considerably lower than the others. This is reasonable when it is considered there is a negative pressure under the fuselage base and probably a considerable spanwise component to the jet flow.

A survey of the total pressure at the nozzle is presented in Figure 19. It is evident from this plot, especially at the wing roots, that there is no internal ducting in the model. Pressures in the wing jets are only about 25% the fuselage jet pressures and are negative near the wing roots. This survey was taken with all slots open and at an $^{h}/mac$ of infinity.

V. Conclusions

1) The cruciform configuration is stable in hover with all blowing surfaces open.

2) Even non-blowing surfaces seem to aid hovering stability. It would seem this is an excellent area for further research.

3) Through the use of wing surfaces (either blowing or non-blowing) it seems to be possible to avoid the hover height decay with forward speed often observed with other configurations.

4) From a performance point of view it is thought that full wing blowing is not likely to be worthwhile unless the wings could be as close to the ground as the fuselage.

5) If the wings were to be higher off the ground than the fuselage, a non-blowing wing on a blowing fuselage has a great deal to recommend it.

VI. References

1. Sweeney, T. E. and Nixon, W. B., The Effect of Planform on the Static Characteristics of Peripheral Jet Wings, Princeton University, Report No. 524, November 1961.

2. Strand, Royce and Fujita, Performance Theory for High Speed Ground Effect Machines, Vehicle Research Corporation, Report No. 11, June 1, 1961.

3. Symposium on Ground Effect Phenomena, Princeton University, October 1959.

VII. Table of Figures

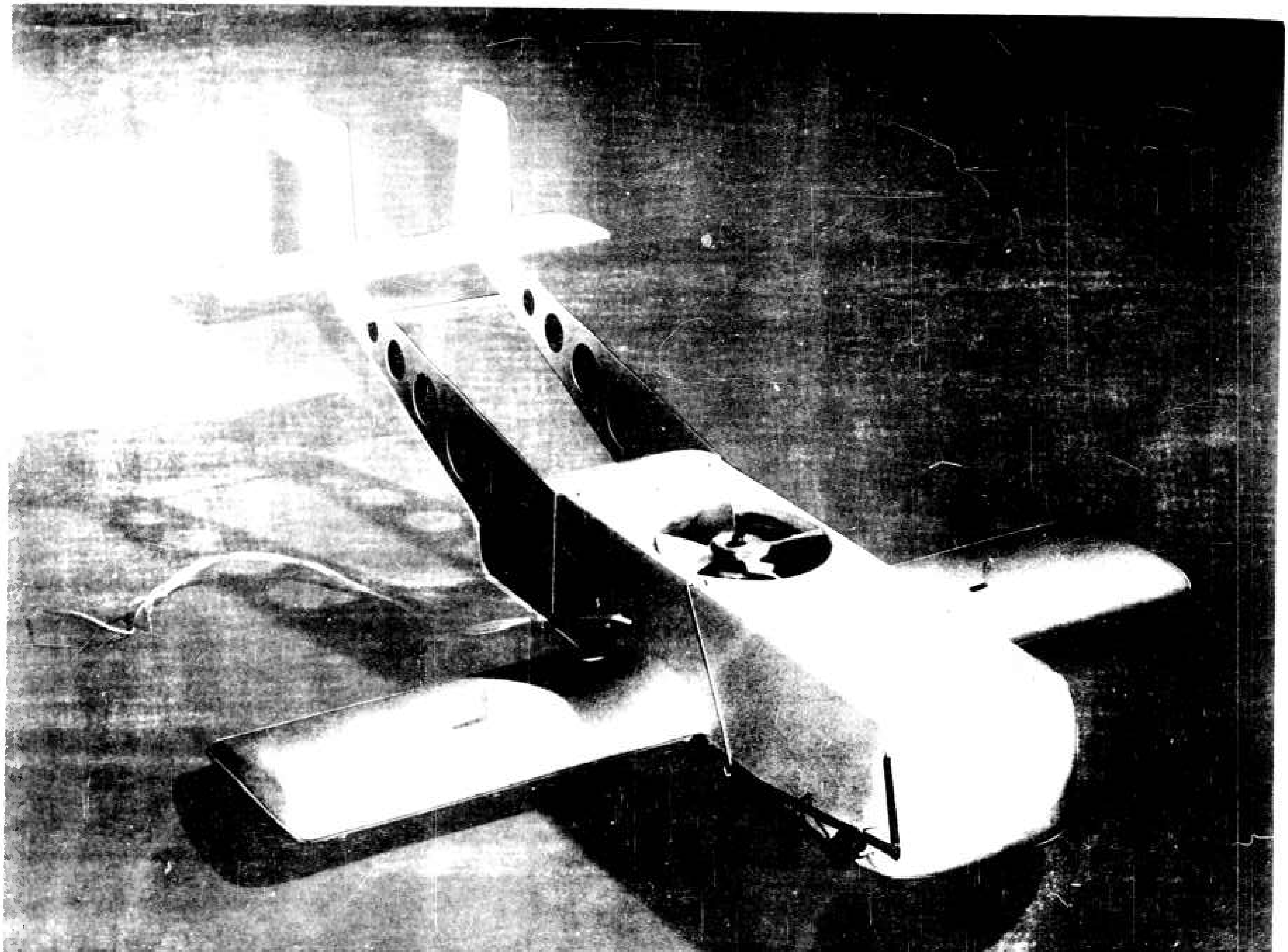


FIG 1

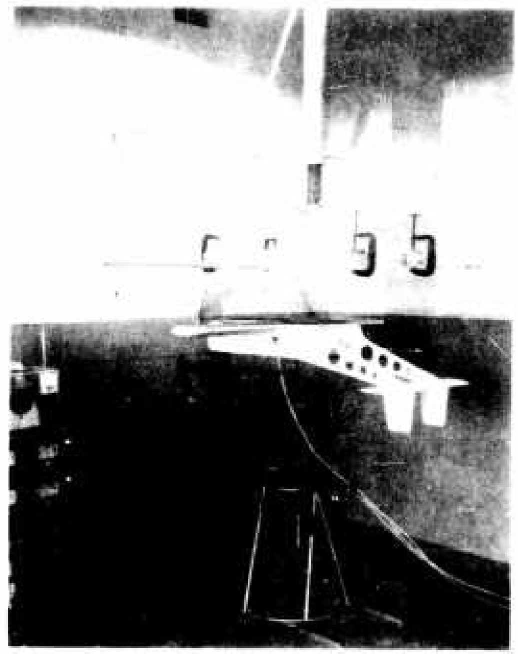


FIG 2

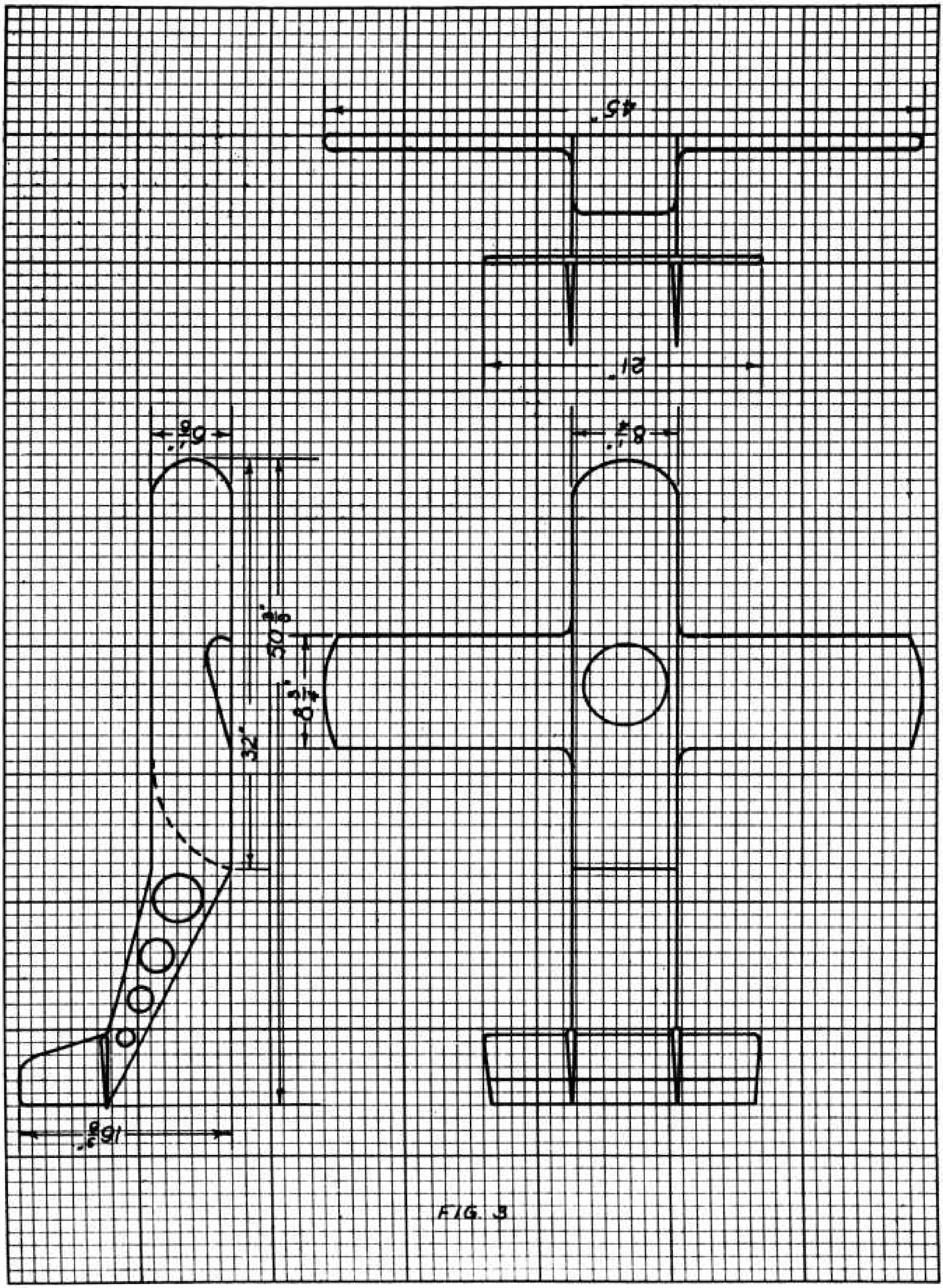
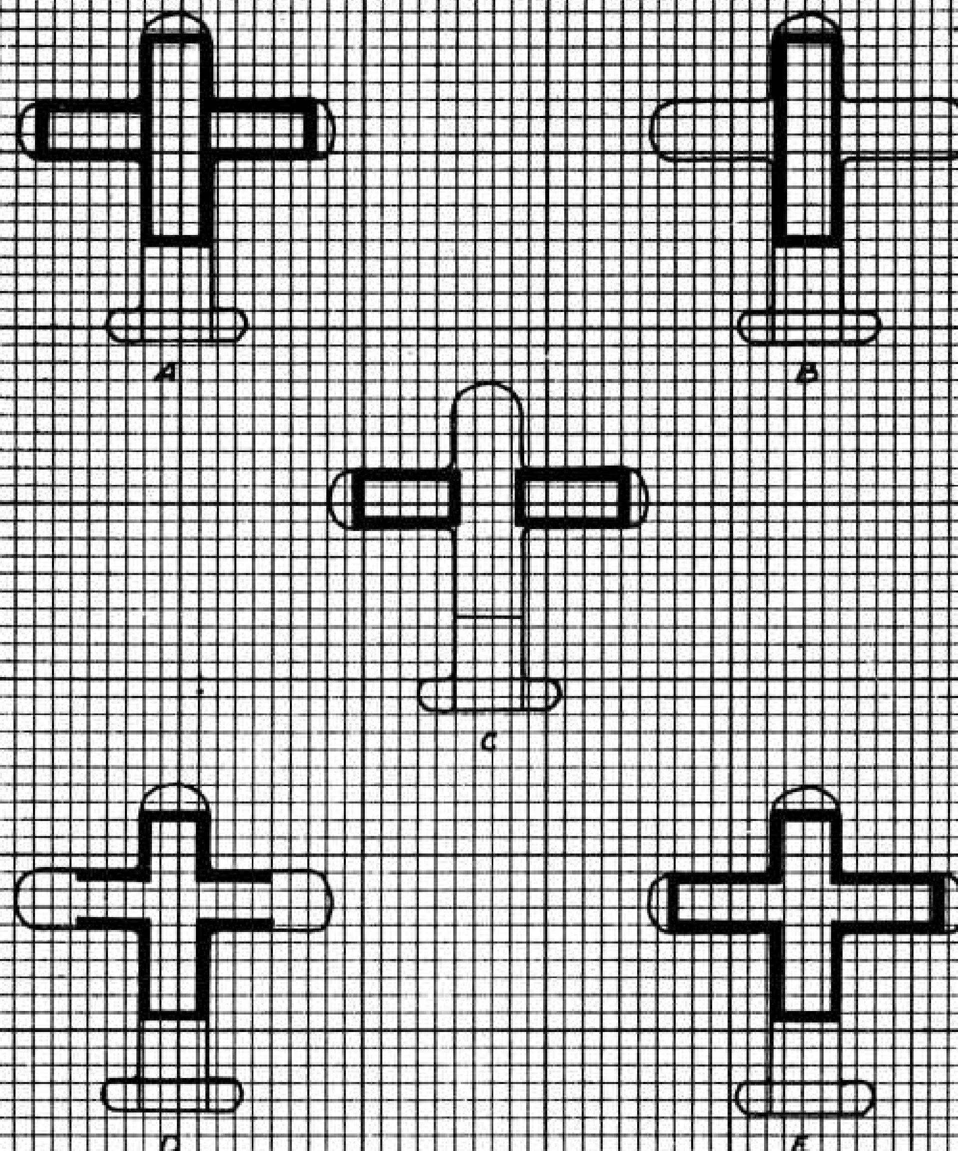


FIG. 3

CONFIGURATIONS TESTED



A ALL SLOTS OPEN
B FUSELAGE SLOTS OPEN
C WING SLOTS OPEN
D OUTER WING AND WING ROOT SLOTS CLOSED
E WING ROOT SLOTS CLOSED

FIG. 4

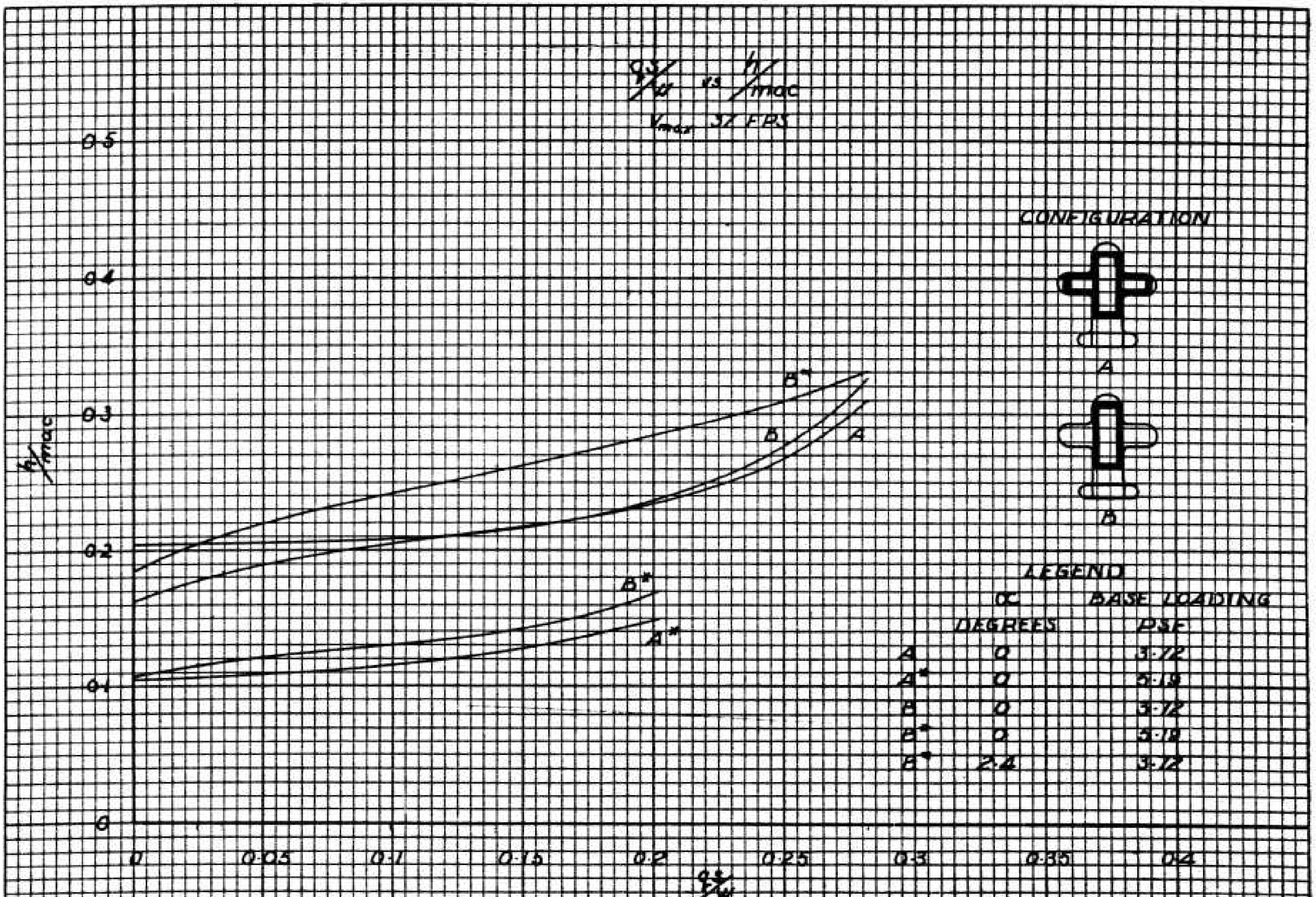
GETOL Performance Table

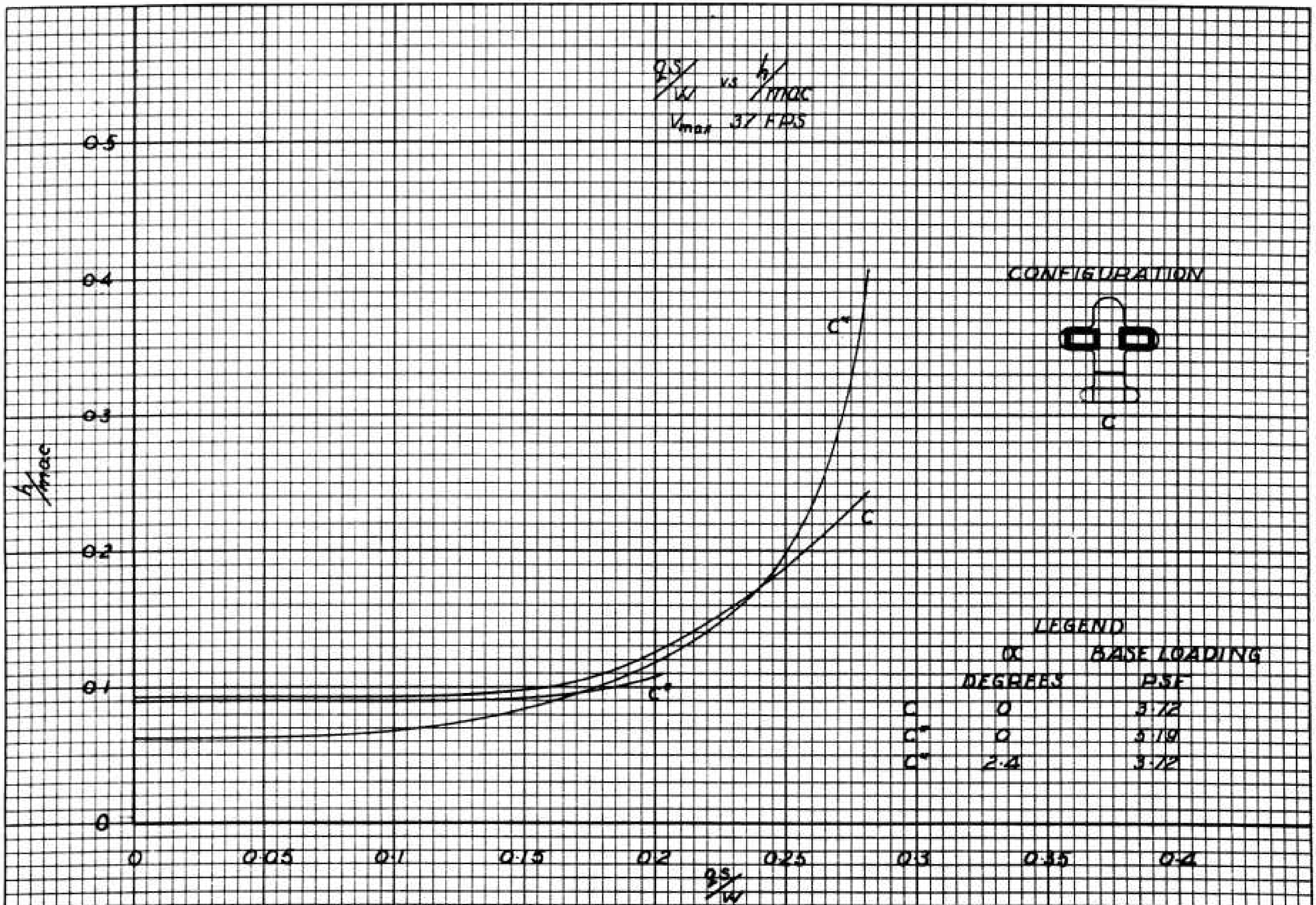
Configuration (see Fig.4)	α Degrees	Hover Alt. $^h/_{mac}$	Maximum Alt. $^h/_{mac}$	Estimated C_μ	Max. Velocity $^{ft}/_{sec}$
A	0	.162	.310	.226	37
A*	0	.106	.150	.226	"
B^α	2.4	.187	.330	.296	"
B*	0	.108	.170	.296	"
B	0	.203	.326	.296	"
C^α	2.4	.061	.408	.219	"
C*	0	.090	.110	.219	"
C	0	.093	.243	.219	"
D	0	.235	.474	.252	"
D*	0	.179	.262	.252	"
D^α	2.4	.141	.354	.252	"
E	0	.246	.429	.197	"
E*	0	.187	.251	.197	"
E^α	2.4	.139	.301	.197	"

* Indicates heavy wing loading configuration 5.19 lb/ft^2 all others are 3.72 $^{lb}/_{ft^2}$. Area used in computing these is the total base area of the model.

α Angle of attack + 2.4 degrees

Fig. 5


qS/W vs h/mac
V_{max} 37 FPS
CONFIGURATION
A
B
LEGEND
α DEGREES
BASE LOADING PSF
A 0 3·72
A* 0 5·19
B 0 3·72
B* 0 5·19
B* 2·4 3·72
A
B
B*
A*
B*
h/mac
0·5
0·4
0·3
0·2
0·1
0
0
0·05
0·1
0·15
0·2
0·25
0·3
0·35
0·4
qS/W
FIG 6



qS/W vs h/mac
V_{max} 37 FPS
CONFIGURATION
C
LEGEND
α DEGREES
BASE LOADING PSF
C 0 3.72
C' 0 3.19
C" 2.4 3.72
0
0.1
0.2
0.3
0.4
0.5
h/mac
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
qS/W

FIG. 7

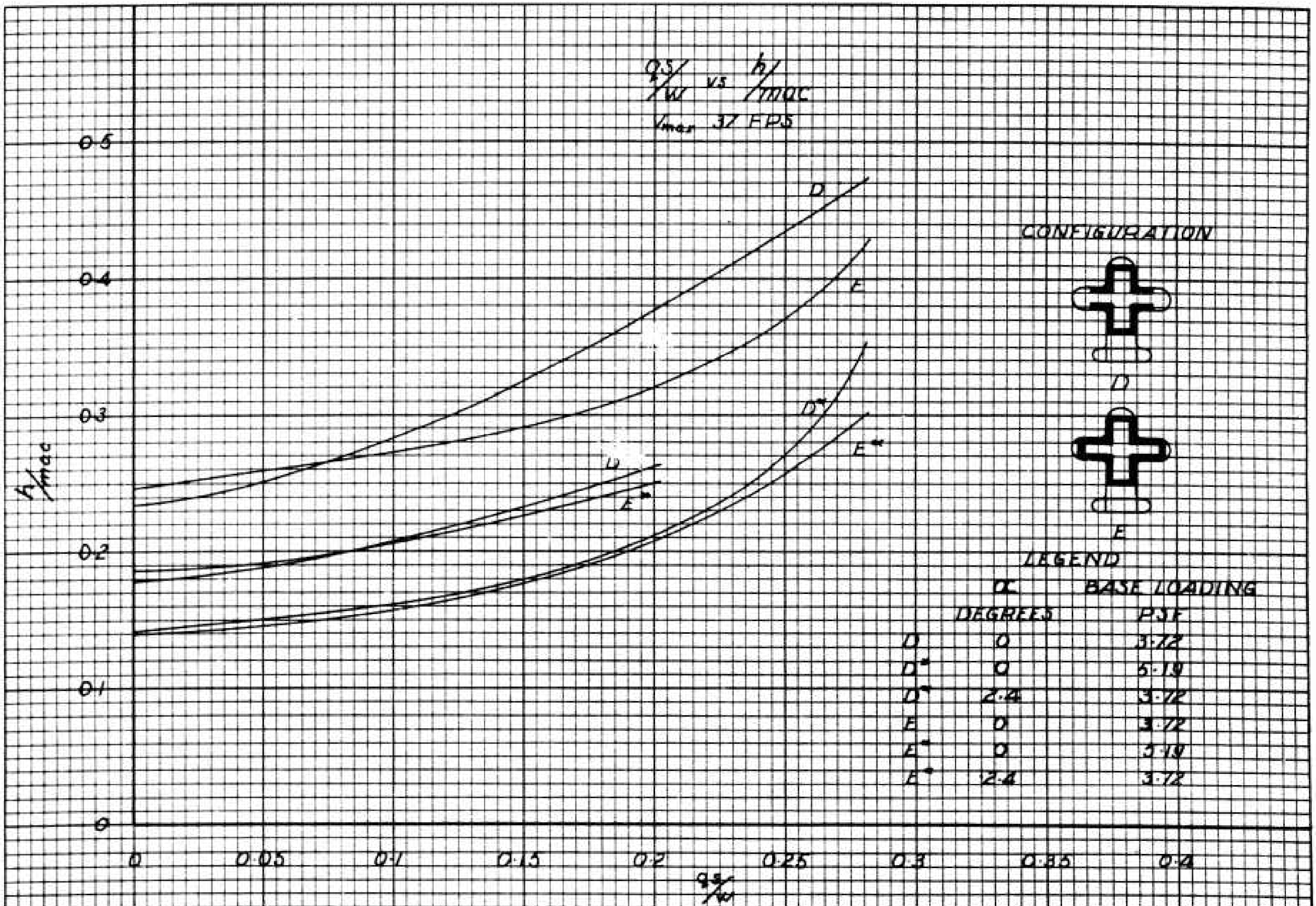

qS/W vs h/mac
Vmax 37 FPS
h/mac
0.5
0.4
0.3
0.2
0.1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
qS/W
D
E
D*
E*
CONFIGURATION
D
E
LEGEND
α DEGREES
BASE LOADING PSF
D 0 3.72
D* 0 5.19
D* 2.4 3.72
E 0 3.72
E* 0 5.19
E* 2.4 3.72

FIG. 8

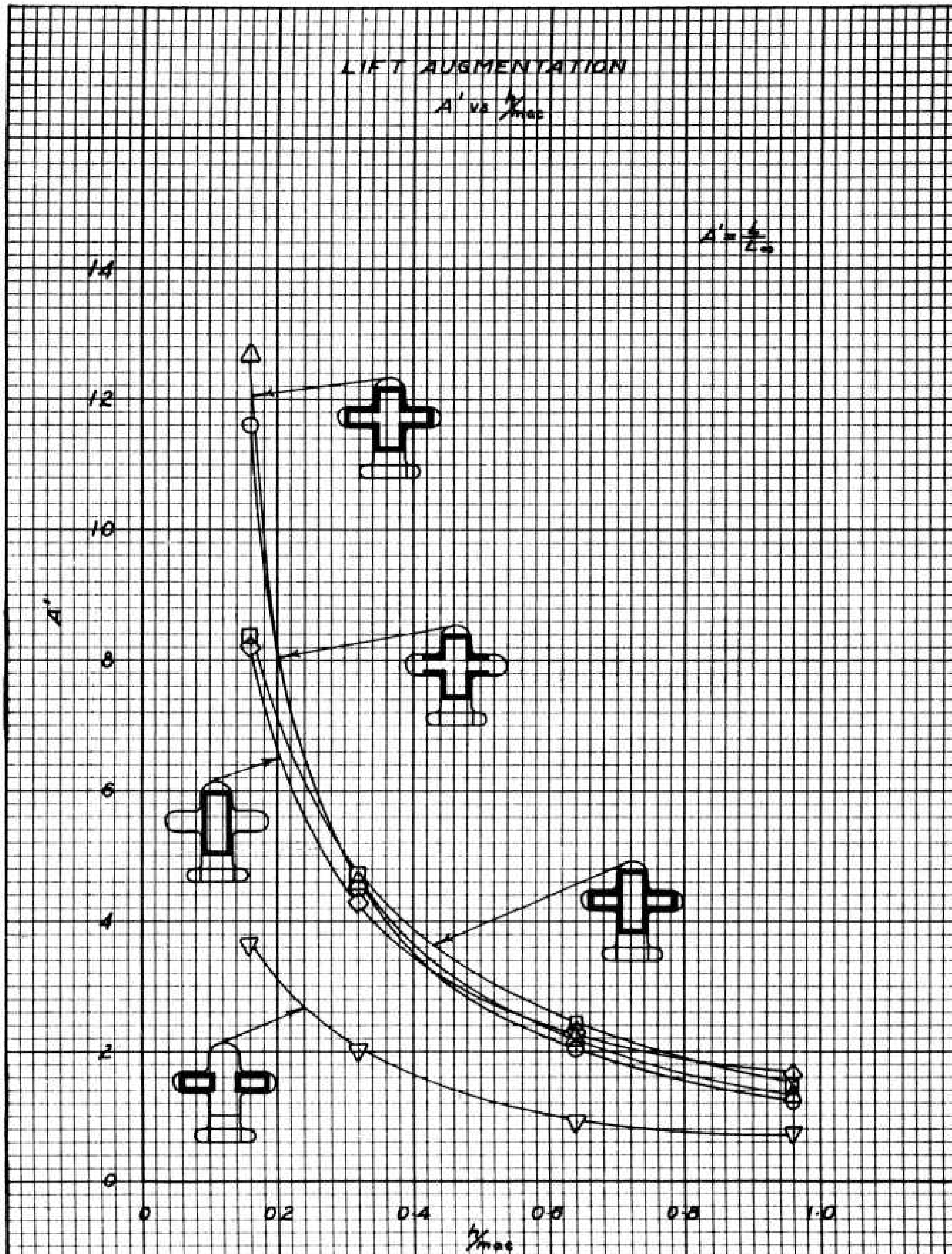

LIFT AUGMENTATION
A' vs h/mac
A' = L/L∞
A'
14
12
10
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1.0
h/mac

FIG. 9

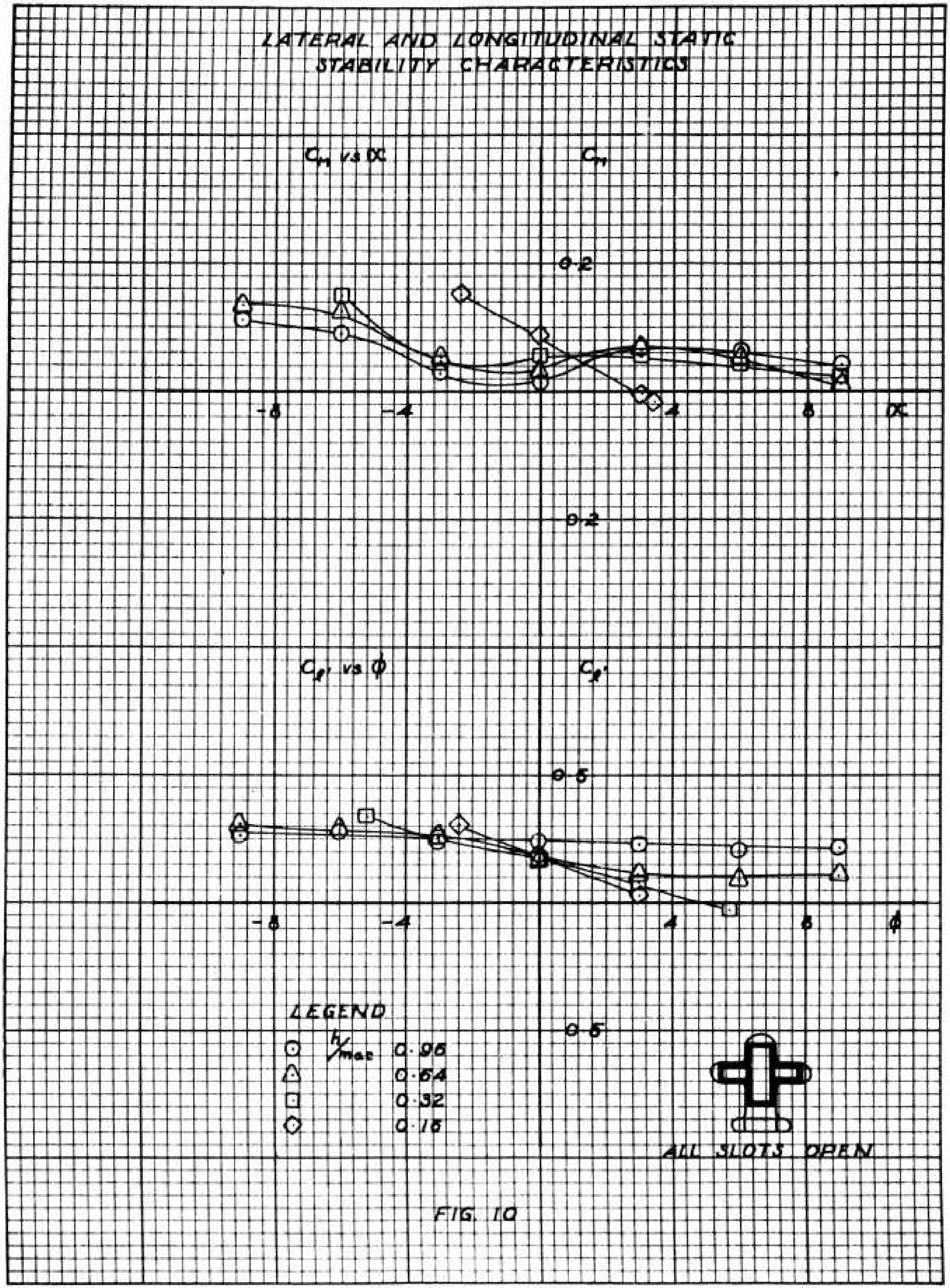

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
C_n vs α
C_n
0.2
-8
-4
4
8
α
0.2
C_l' vs ϕ
C_l'
0.5
-8
-4
4
8
ϕ
0.5
LEGEND
h/max
0.96
0.64
0.32
0.16
ALL SLOTS OPEN

FIG. 10

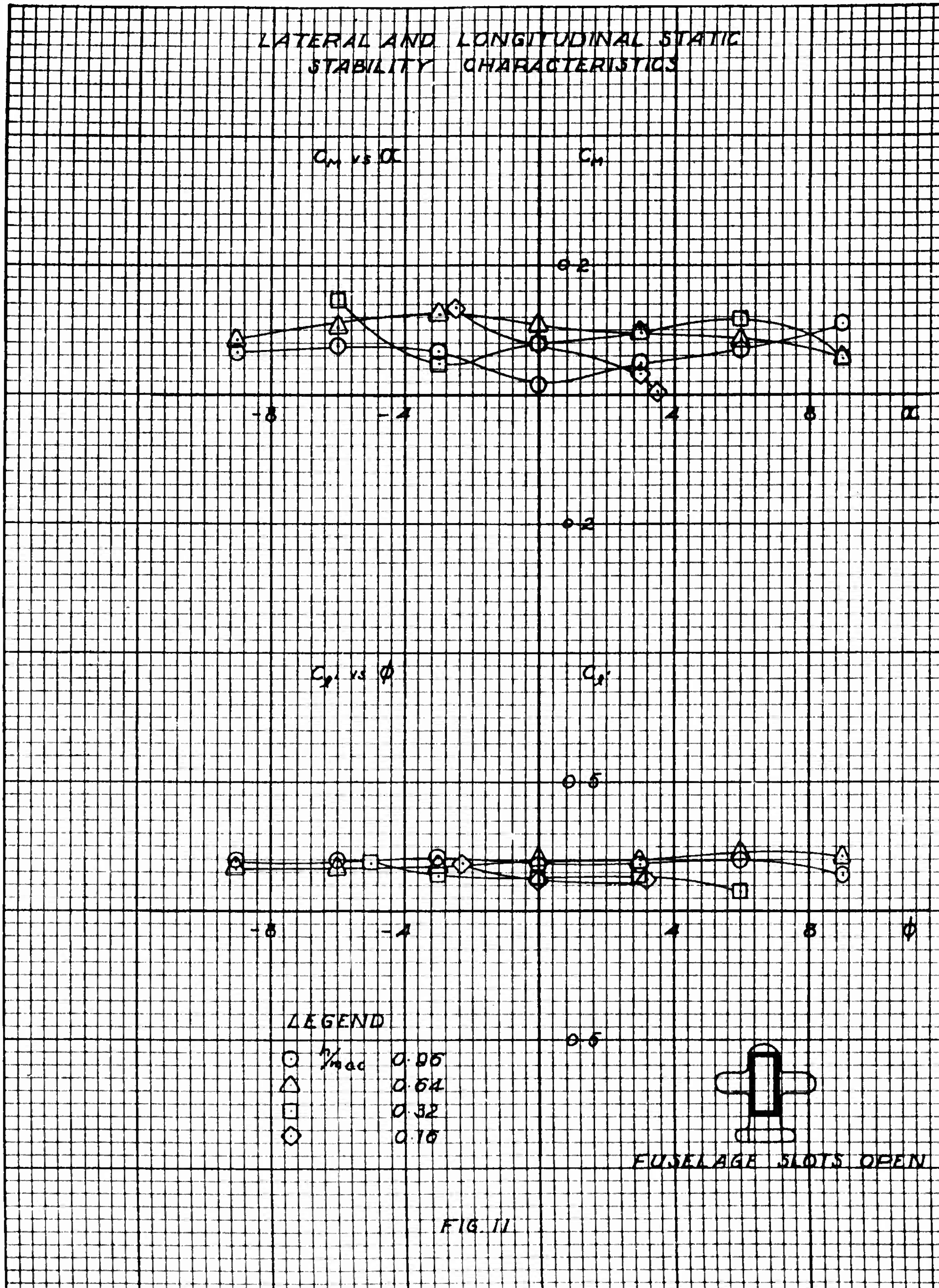

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
C_M vs α
C_M
0.2
-8
-4
4
8
α
0.2
$C_{l'}$ vs ϕ
$C_{l'}$
0.5
-8
-4
4
8
ϕ
LEGEND
h/mac
0.96
0.64
0.32
0.16
0.5
FUSELAGE SLOTS OPEN

FIG. 11

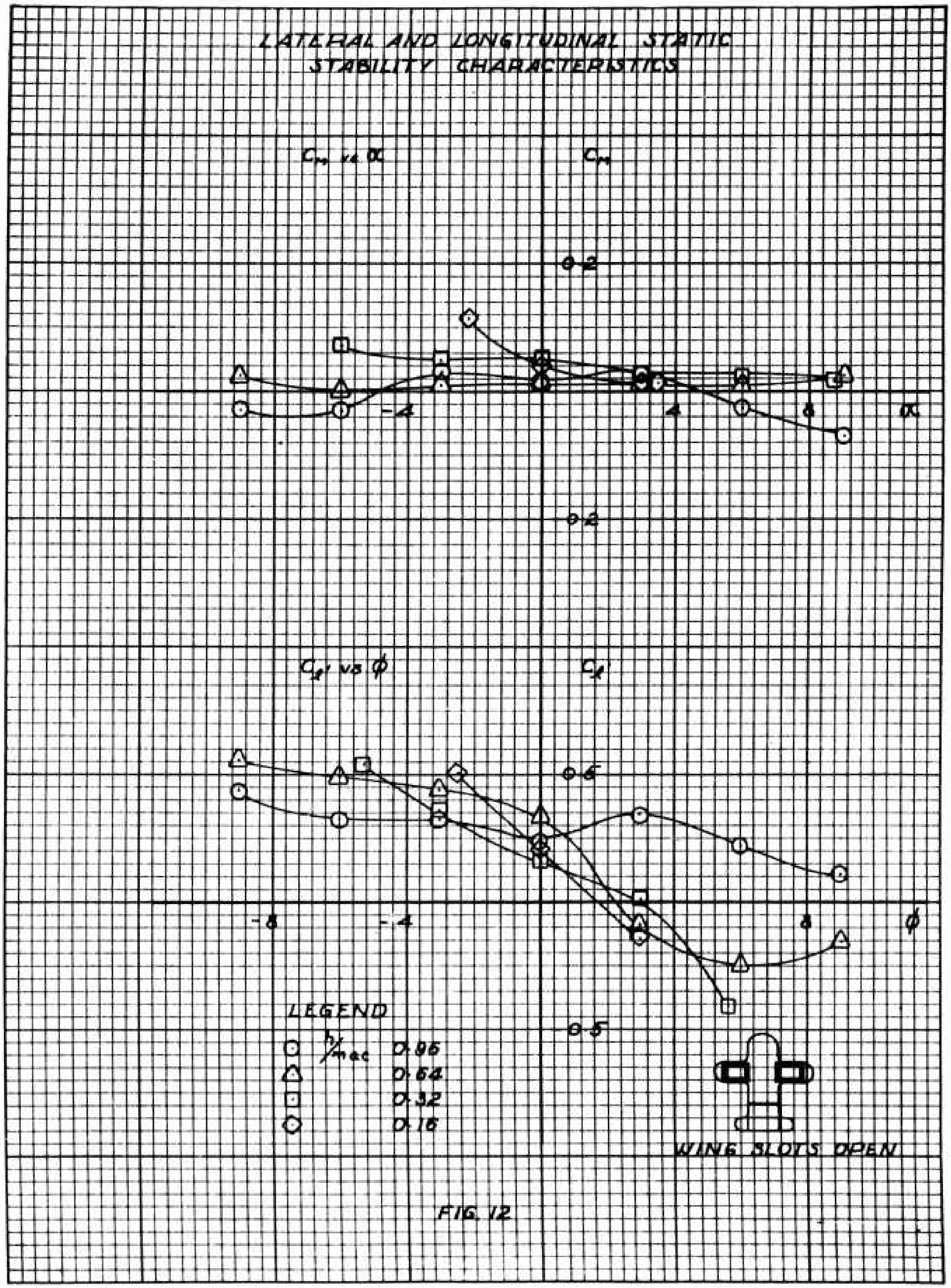

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
Cm vs α
Cm
0.2
-4
4
8
α
0.2
Cℓ' vs φ
Cℓ
-8
-4
8
φ
LEGEND
h/mac
0.96
0.64
0.32
0.16
WING SLOTS OPEN

FIG. 12

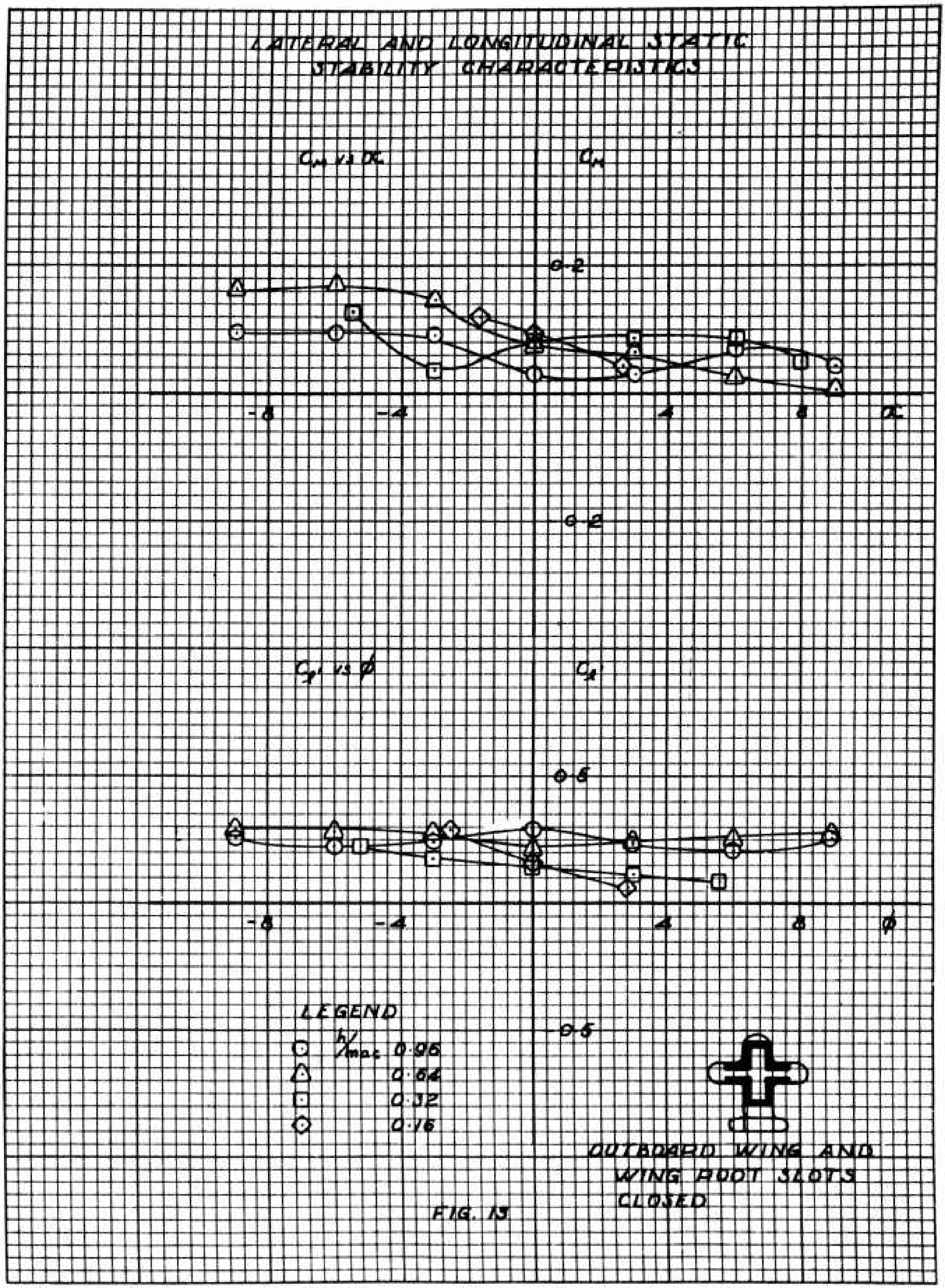

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
C_M vs α
C_M
0·2
-8
-4
4
8
α
0·2
C_l' vs φ
C_l'
0·6
-8
-4
4
8
φ
0·6
LEGEND
h/mac
0·96
0·64
0·32
0·16
OUTBOARD WING AND
WING ROOT SLOTS
CLOSED

FIG. 13

LATERAL AND LONGITUDINAL STATIC STABILITY CHARACTERISTICS

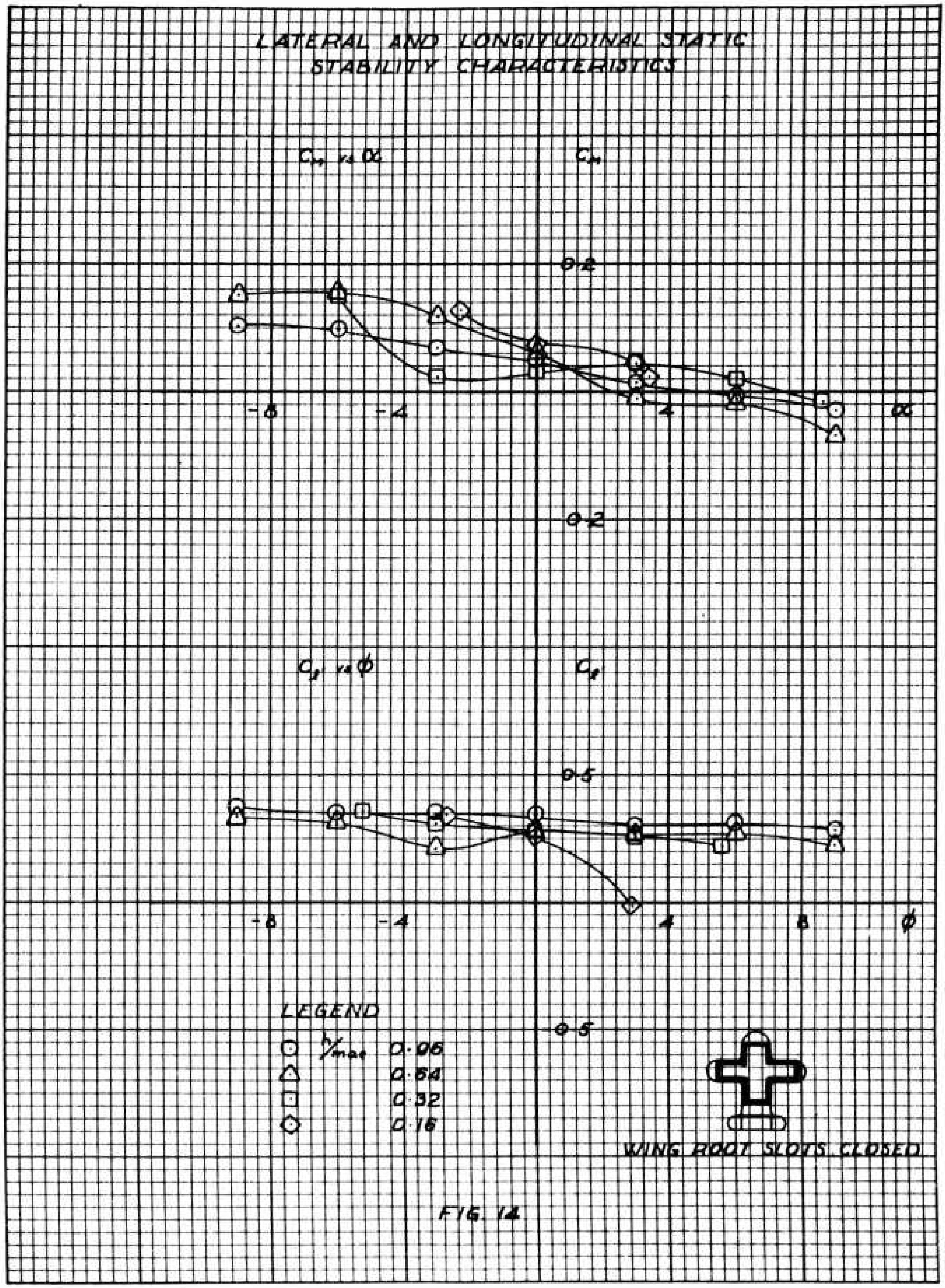


FIG. 14

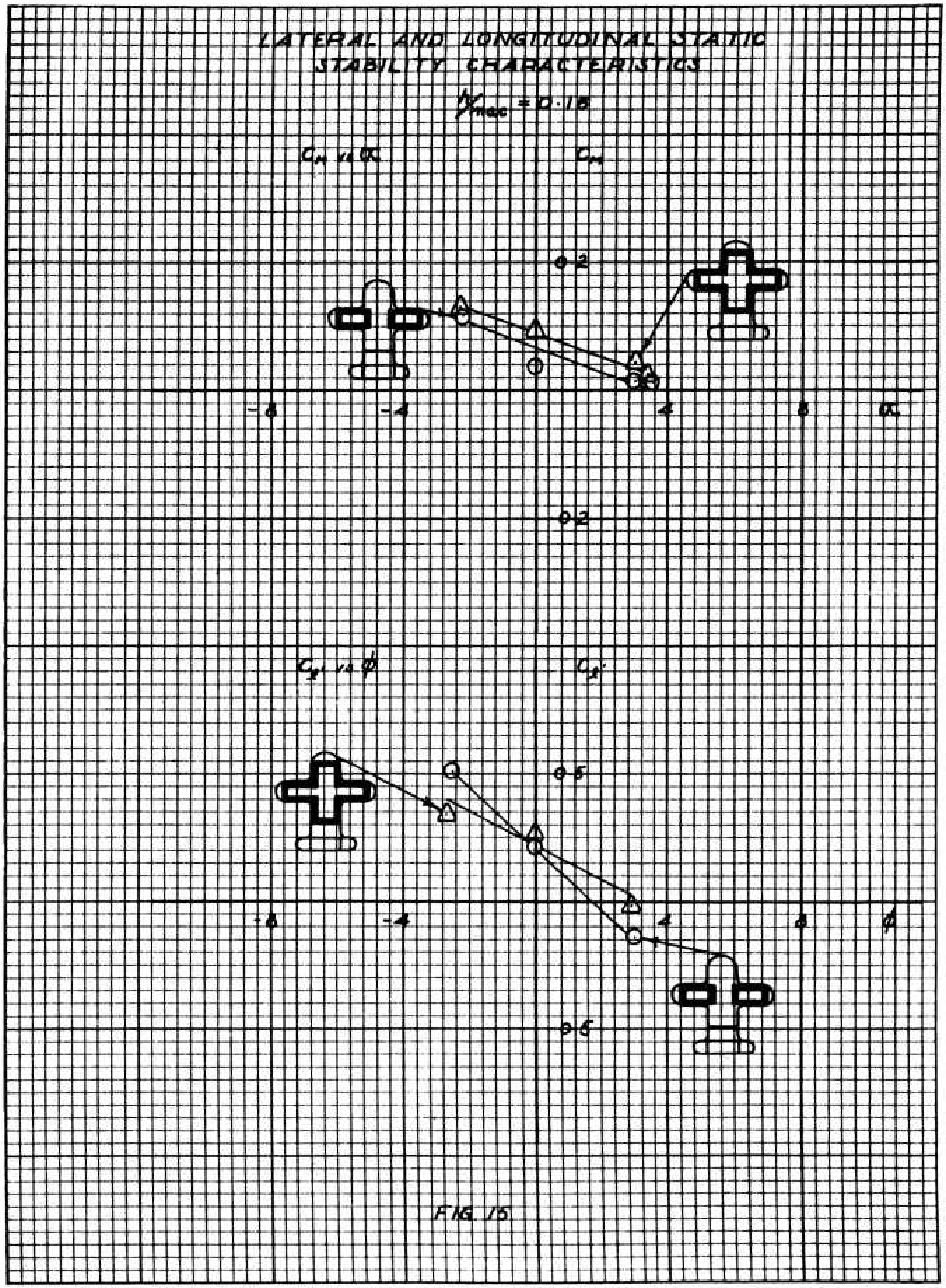
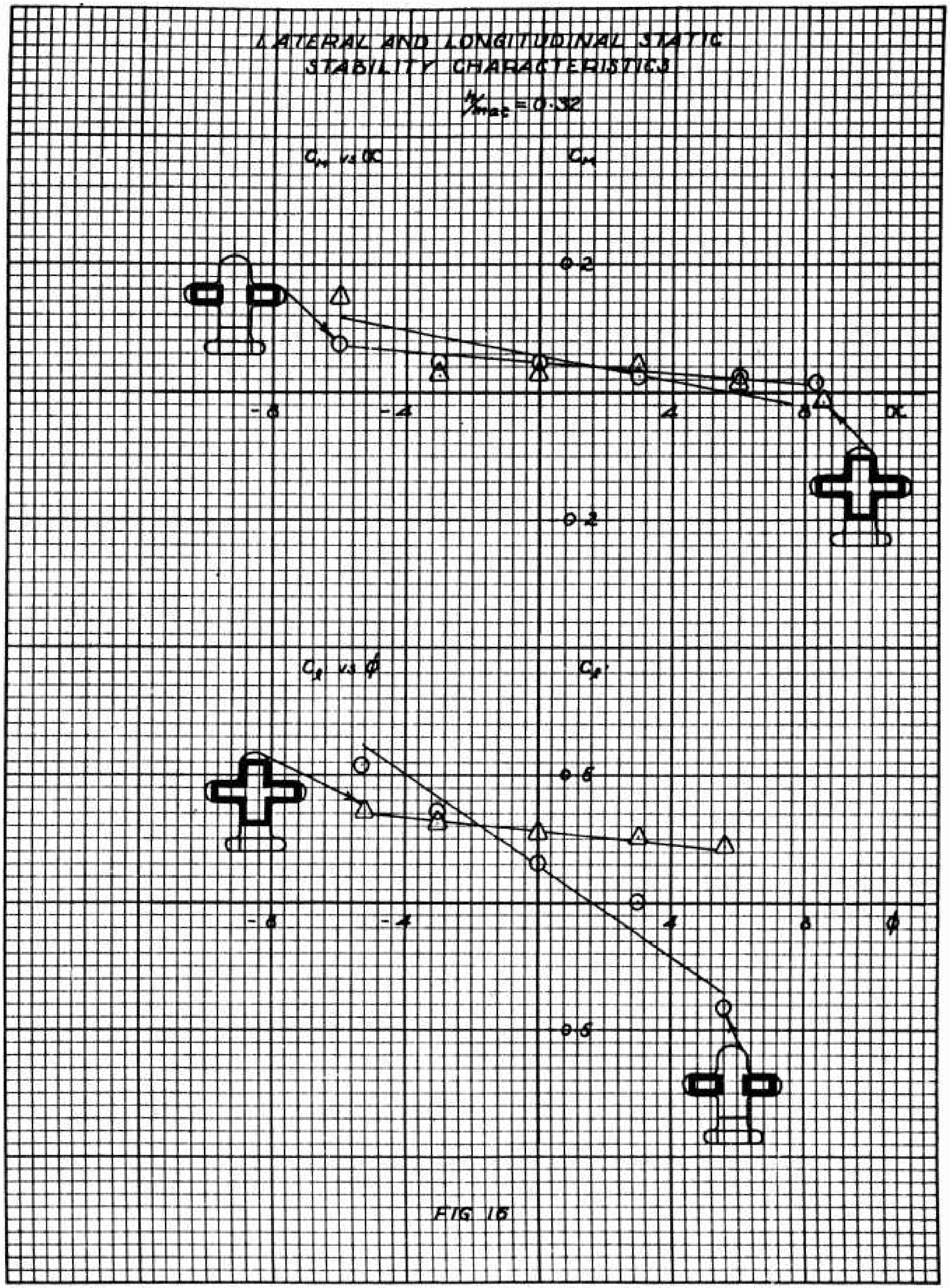

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
h/mac = 0.15
CM vs α
CM
0.2
-8
-4
4
8
α
0.2
Cl' vs φ
Cl'
0.5
-8
-4
4
8
φ
0.5

FIG. 15


LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
H/mac = 0·32
Cm vs α
Cm
0·2
-8
-4
4
8
α
0·2
Cℓ vs φ
Cℓ
0·6
-8
-4
4
8
φ
0·6
FIG 16

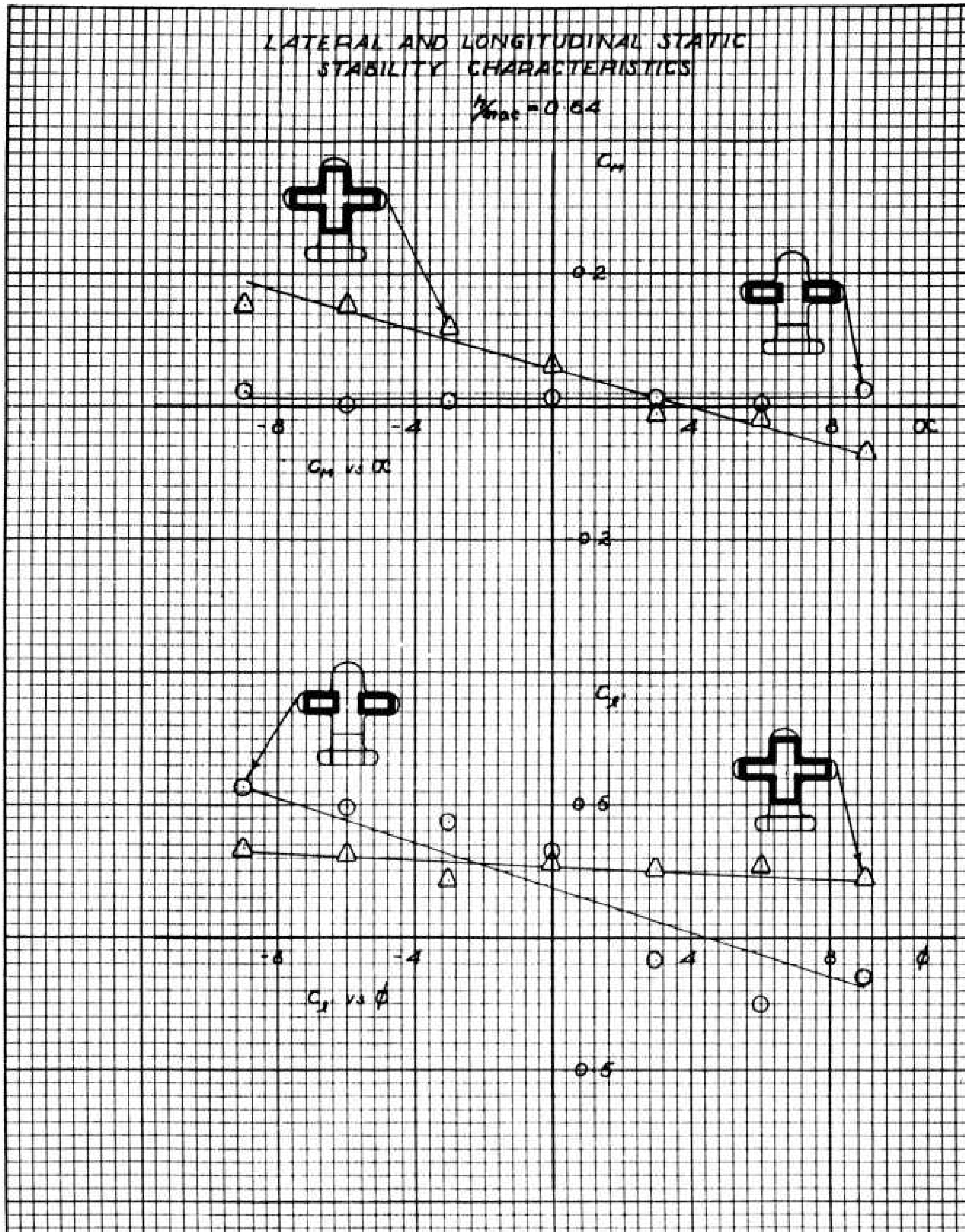

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
h/c mac = 0.64
C_M
0.2
-8
-4
4
8
α
C_M vs α
0.2
C_ℓ
0.6
-8
-4
4
8
φ
C_ℓ vs φ
0.6

FIG. 17

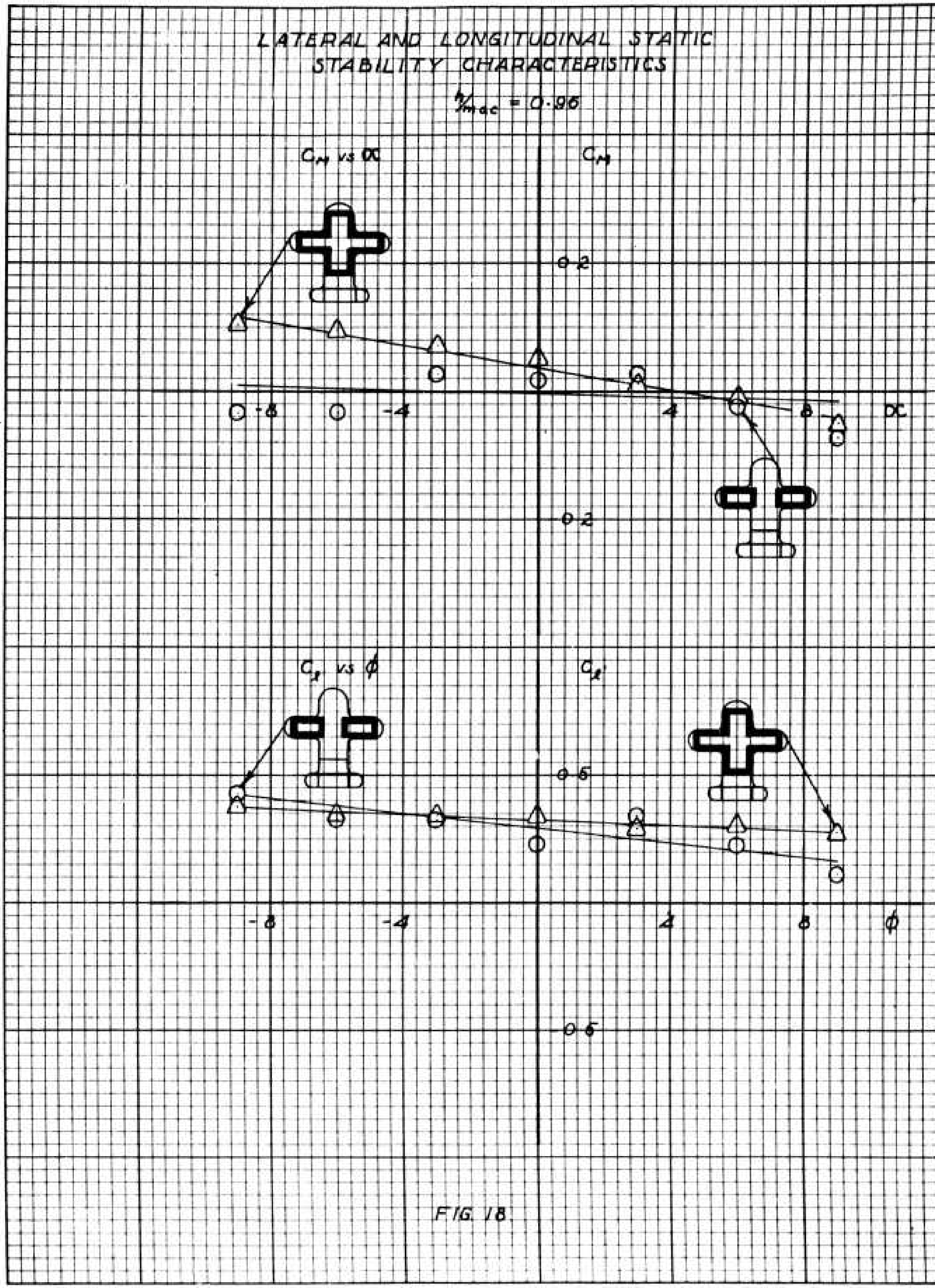
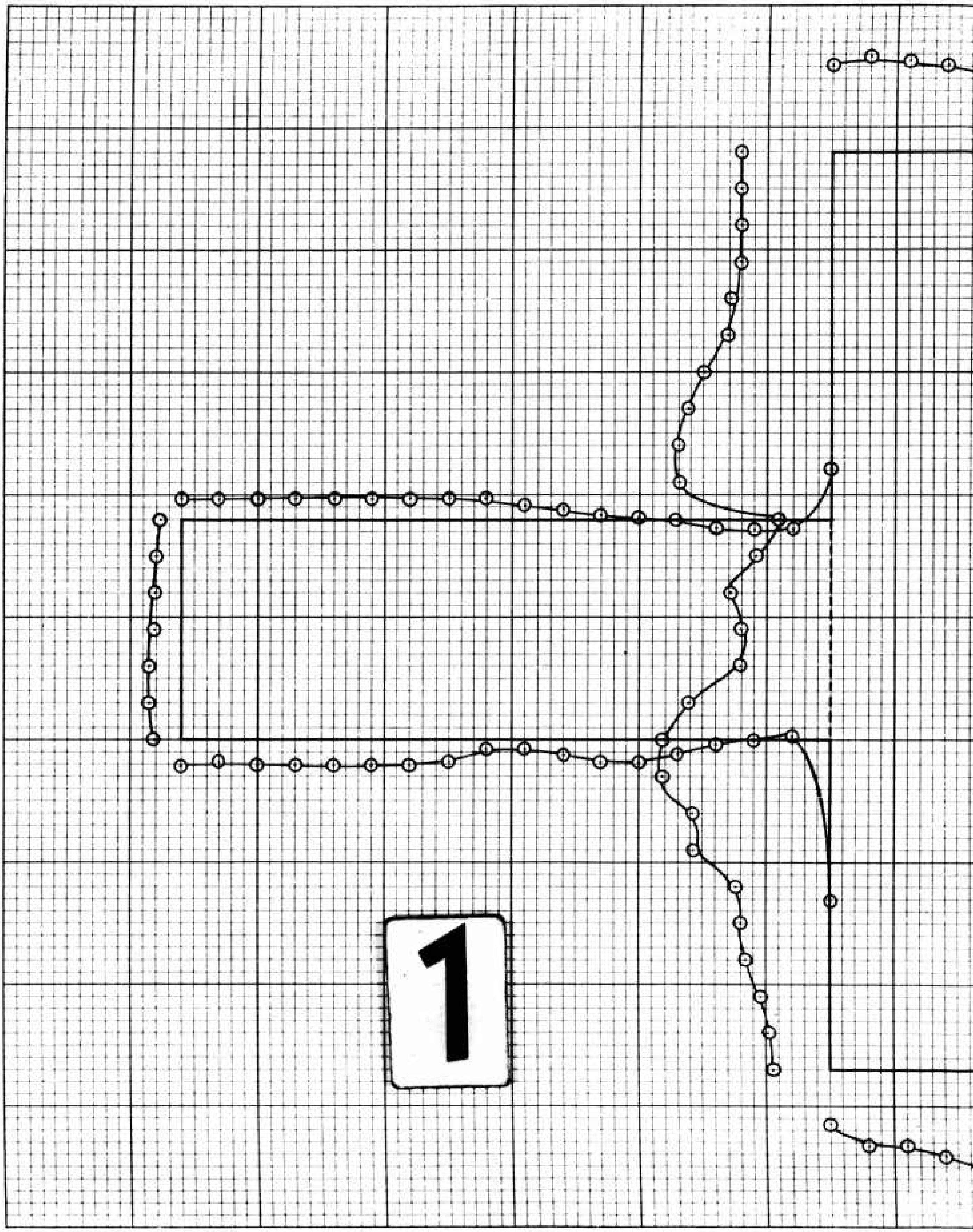

LATERAL AND LONGITUDINAL STATIC
STABILITY CHARACTERISTICS
h/mac = 0·96
C_M vs α
C_M
0·2
-8
-4
4
8
α
-0·2
C_ℓ vs ϕ
C_ℓ
0·5
-8
-4
4
8
ϕ
-0·5

FIG. 18



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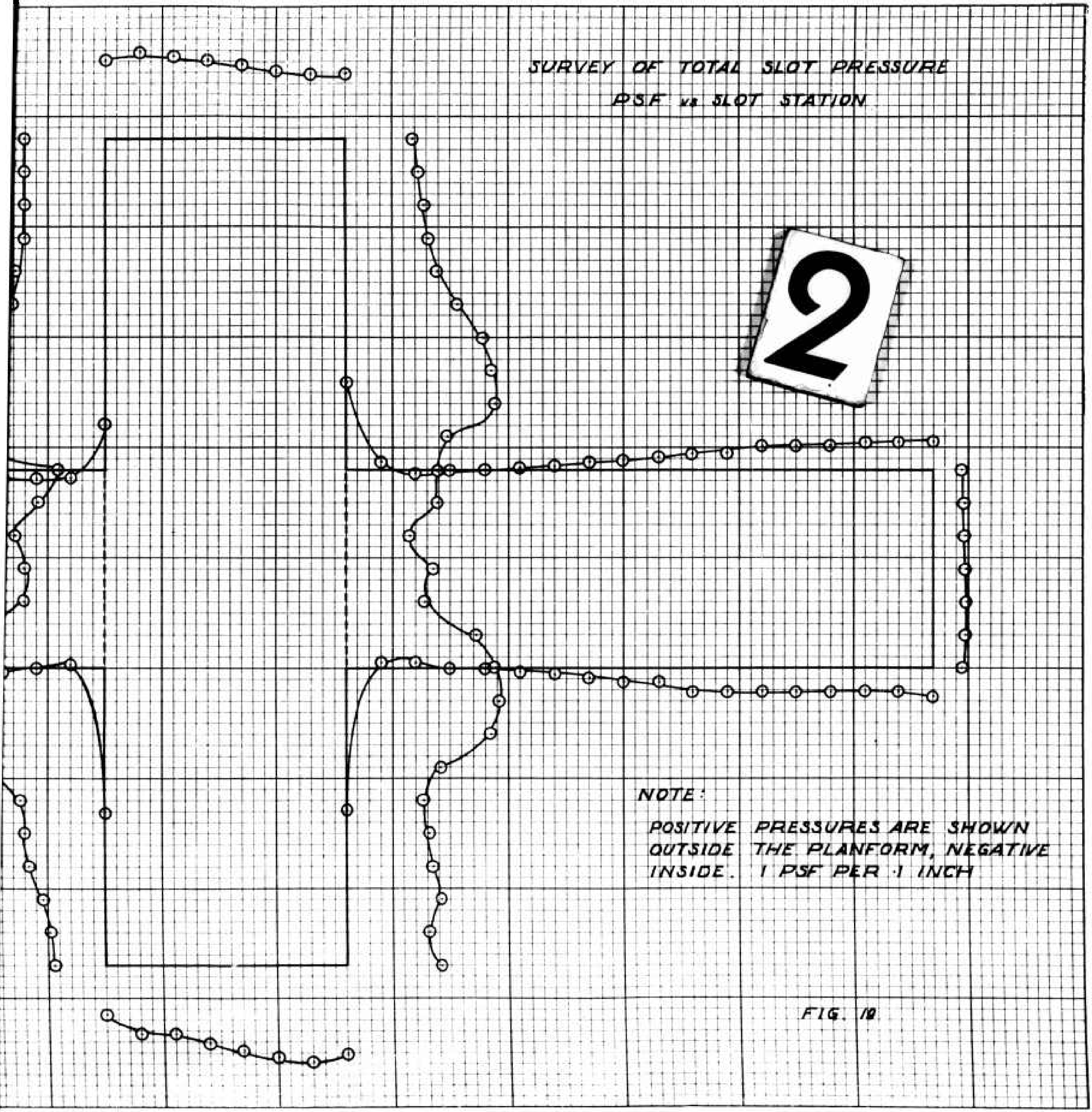

SURVEY OF TOTAL SLOT PRESSURE
PSF vs SLOT STATION
2
NOTE:
POSITIVE PRESSURES ARE SHOWN OUTSIDE THE PLANFORM, NEGATIVE INSIDE. 1 PSF PER 1 INCH

FIG. 10

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Princeton University Aero. Eng. Dept., Princeton, N. J.

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- M. P. Knowlton and D. Summers

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3. Airplanes - Ground Effects
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A GETOL model utilizing ground effect under the fuselage and wings was tested on the Princeton University Long Track Facility and on a static test stand.

The model, free in hover, was slowly accelerated to a speed of 37 feet per second while its change in altitude was measured. There was no altitude loss observable at any point during the runs for the configurations tested.

The static tests indicate both pitch and roll stability up to $^h/_{mac}$ ratios of .96, the maximum tested. Of prime interest is the fact that both roll and pitch stability are increased by the addition of non-blowing wings (for roll) and no fuselage blowing (for pitch) over what would normally be expected of a GEM without wings.

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